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SIMULATION OF HIGH-RATIO COMPRESSION OF A PARALLELEPIPEDAL DURALUMIN BAR USING THE PARTICLE-BASED METHOD AND MSC.ADAMS SOFWARE

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Summary: *The work consists of the two parts: the experiment part and the calculation part. In the experiment part, the 30×10×10 (mm) duralumin bar is subjected to high-ratio compression using a laboratory machine. The experiment compression curve is obtained. The calculation model of the duralumin bar is made of a relatively small number of particles (macro-molecules). The theoretical macro-molecule force characteristic is selected under condition, that the bar calculation compression curve and the bar experiment compression curve are as close as possible.*

INTRODUCTION

Duralumin was invented by the German engineer Alfred Wilm in 1903 [1]. Now it is a widely used structural material [2]. But its application area (except for special practices, such as plastic shock-absorption [3], etc.) is mostly limited by the elastic segment of the load curve. Bearing capacity of a structural material may be increased several times by implementing particle-based methods for computer simulation of its high-ratio deformations. The compression is a high-ratio one, if the characteristic relative displacement is about 20%.

The particle-based methods are developed mainly for liquids and granular (powder) materials [4,5]. This approach has a great potential for solid structures [6]. It does not require using the available continuity hypothesis of deformable solids. This approach does not make difference between elasticity and plasticity. It does not require using old concepts of stress, strain and temperature. It makes it possible to look at the actual problems of mechanics from another side.

In this work the duralumin bar is considered as a set of relatively small number of particles arranged in the nodes of a design lattice. The particle is taken as a macro-molecule

(hereinafter referred to as just a molecule) like that in molecular physics. Solution of the specified compression problem is reduced to integration of dynamic equations of the considered set of molecules (moving successively from one equilibrium state to another) and to monitoring their behavior.

EXPERIMENT

This work consists of the two parts: the experiment part and the simulation part. Figure 1 specifies the compression experiment. The duralumin 30×10×10 (mm) specimen is arranged between the two compression plates of the laboratory machine. The upper plate goes down. The bottom plate is fixed. The loading process is slow, it has a so called "static" character. The considered laboratory assembly has a clearance in the loading direction. The clearance is taken up at the beginning of the loading procedure.

Figure 1: The duralumin bar is arranged between the two compression plates of the laboratory machine

The experiment set includes 5 specimens. All of them are cut from the same piece of duralumin and processed by milling. So, there are milling scratch lines on the faces of each

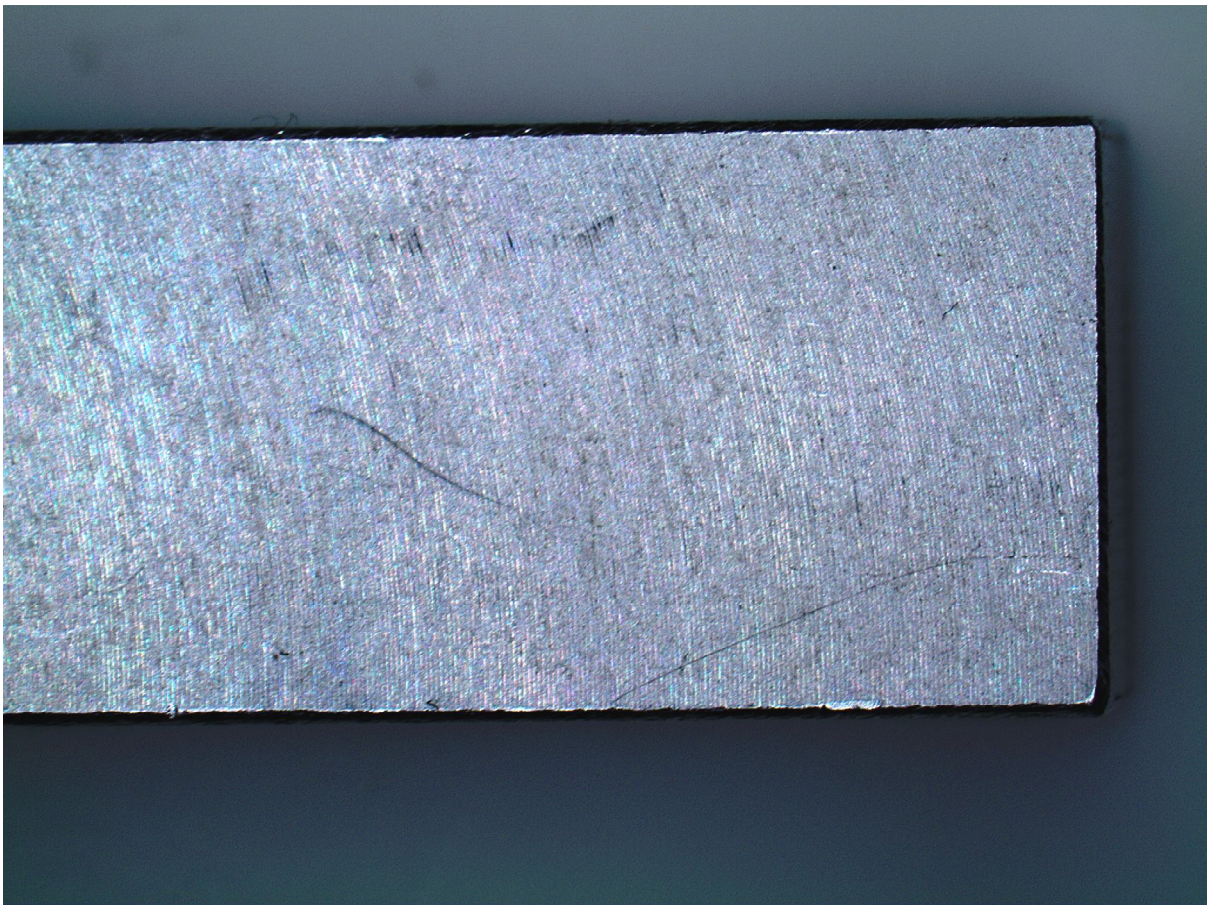

Figure 2: Milling scratch-lines (line defects) are available on the face of the duralumin specimen

specimen. These scratch lines are examined using an electronic microscope. Their photo is presented in figure 2. They may be considered as the line defects. Together with internal material defects, geometric errors, nonparallelism of the working surfaces of the two compression plates of the laboratory machine, misalignment error of the direction of the applied compression load, etc. they may affect essentially the bar compression process.

In all cases the bar deformation character is similar. The front view and the top view of the compressed specimen (turned through 90º in relation to their position in the laboratory machine) are specified in figure 3. Each specimen suffers folding and buckling. The folding process precedes the buckling one. The fold line is right in the middle. The characteristic streamlines are well seen in figure 3 on the specimen face. The streamline curvature is small in the vicinity of the right and the left contacting faces. The streamline curvature has its maximum value in the vicinity of the fold crust. The contacting faces remain flat, but their area widens during compression mainly at the expense of the additional pressed-out material. So, the bar most strained zone is in the vicinity of the contacting faces.

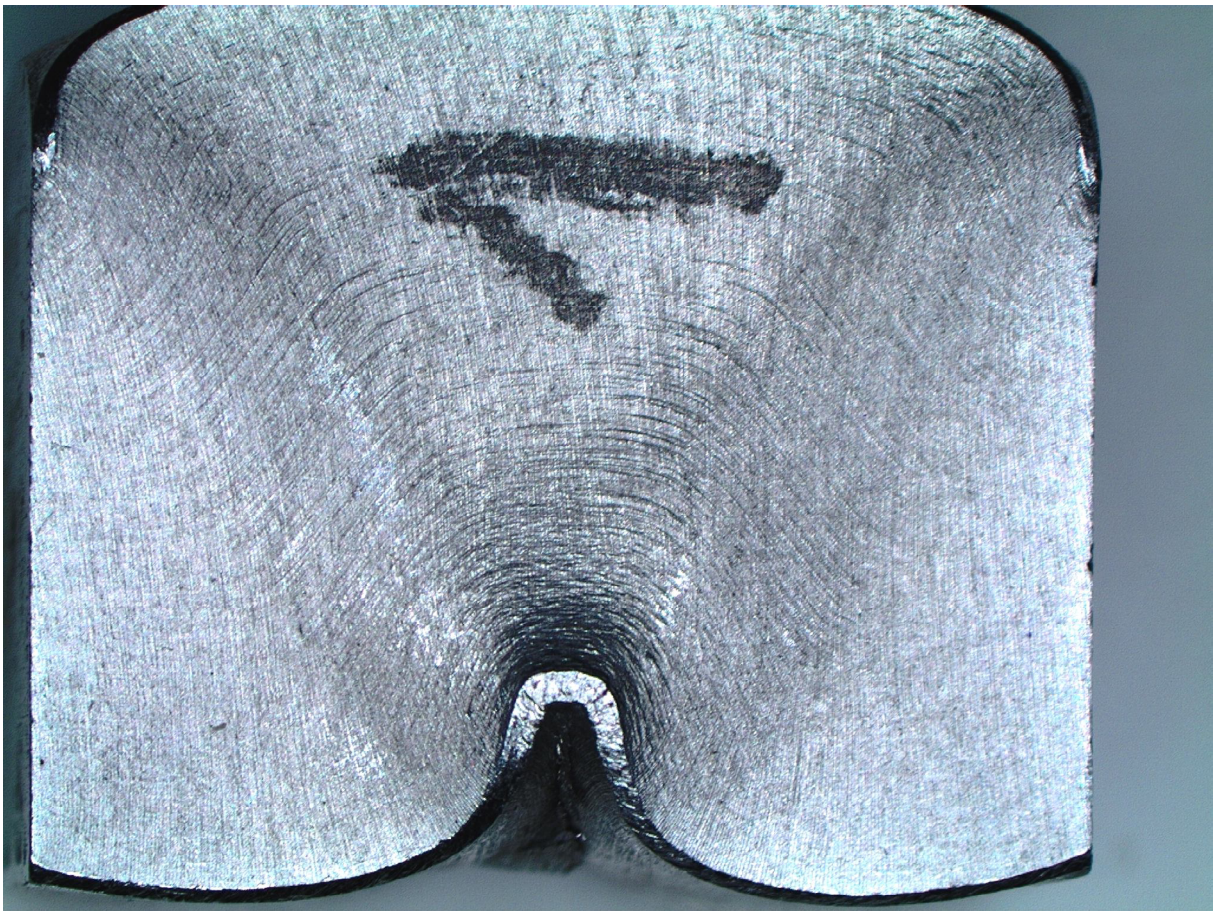

Figure 3: Folding and buckling of the compressed specimen. Front view (turned through 90º in relation to its position in the laboratory machine). Compression ratio is about 40%.

The set of the five obtained duralumin experiment compression curves is presented in figure 4. It is the dependence of the compression force of the laboratory machine on displacement of its movable compression plate. The curve random scatter is available. The curves grow monotonically. The obtained total compression ratio is about 40%. The curve No. 3 is selected as the duralumin representative curve of the given set of curves. It is used hereinafter for comparing with the corresponding calculation compression curve. This is the main result of the experiment.

COMPUTER SIMULATION

The computer simulation is carried out using the MSC.Adams software. The considered parallelepipedal bar model is made of a relatively small number of molecules. There are 3 variants: 4×2×2=16 molecules, 7×3×3=63 molecules and 10×4×4=160 molecules. The undeformed 4×2×2=16 simulation model is shown in figure 5. The duralumin molecules

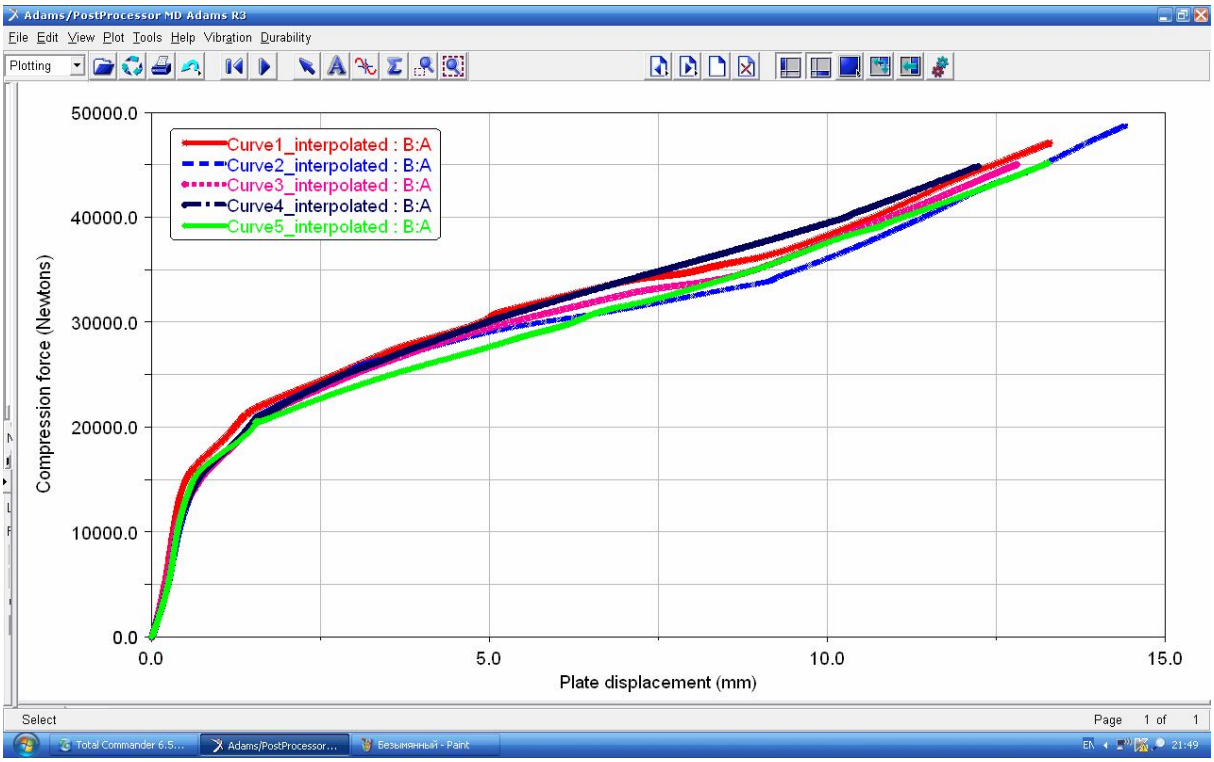

Figure 4: The obtained set of the five duralumin experiment compression curves

are arranged uniformly in the nodes of the design lattice. l – is the lattice spacing. There are two compression plates. The left plate is fixed. The right one moves slowly to the left and provides the required compression. This plate is represented as a wireframe because it may hide the picture. There is the initial 0.1 mm clearance between the bar and each of the compression plates. The molecules interact with each other – "each one with each one".

The interaction links are specified in figure 5 using the conditional interaction lines. Total number of these lines is considerable. For example, for the 10×4×4=160 model, quantity of interaction lines is equal to $n(n\text{-}1)/2=160(160\text{-}1)/2=12720$. So, it is impossible to assemble the simulation model by just picking the screen of the MSC.Adams interface. It is necessary to write a special program using the internal Adams View Command Language (VCL). The two pairs of red molecules (arranged along the longitudinal x-axis) localize the defect line on the bottom face of the bar. To make the defect, the two interaction links of these two pairs are cut (deactivated). Possible rotation of all the molecules is blocked. Only translation is possible. Total mass of the bar is divided between all the molecules. The molecules of the side faces of the bar contact the compression plates of the laboratory machine. It is assumed that friction is too high and they can move only along the x-axis. Contacts in the molecule sphere surfaces are not available. The molecules interact as the point particles.

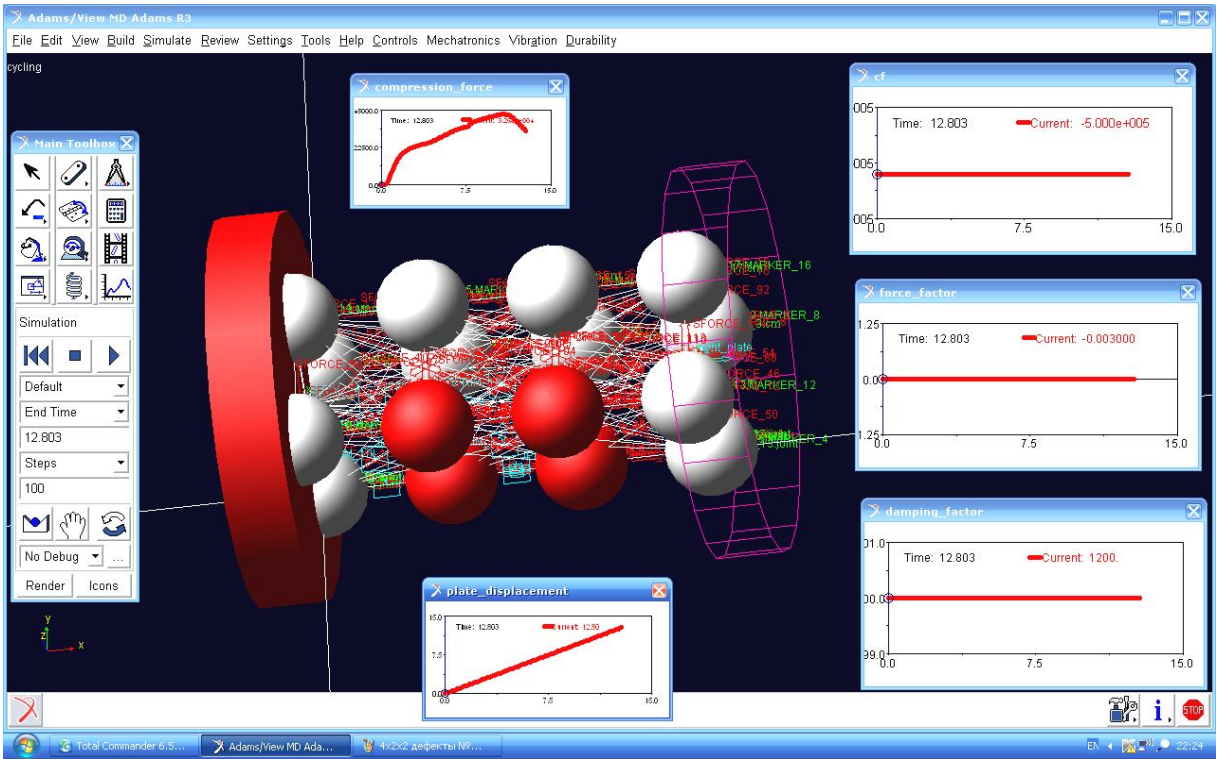

Figure 5: Interaction lines of the 4×2×2=16 bar model (MSC.Adams interface)

The computer simulation shows, that compression (contrary to traditional understanding) is not a monotonous static process. There is the succession of the system equilibrium states and the succession of transitions from one equilibrium state to another. The transients are extremely intensive. So, studying the bar compression process requires generation of equations of the system compression dynamics, setting the Cauchy problem with initial conditions and its proper integration.

The equations of compression dynamics of the considered system of molecules take the following form:

$$\begin{aligned} & -m_j \ddot{\vec{r}}_j - \sum_{\substack{k=1 \\ k \neq j}}^{n} \vec{F}_{jk} + \vec{F}_{jleft} + \vec{F}_{jright} = 0; \\ & j = 1...n; \end{aligned} \tag{1}$$

where: n – is the number of molecules of the system; m_j – is the molecule mass; $\vec{r}_j$ – is the molecule radius vector;

$$F_{jleft} = B\dot{x}_j step(x_j - x_{left}, -1, 1, 0, 0); \tag{2}$$

- is the force of the molecule interaction with the left fixed compression plate of the laboratory machine. The considered integration process is extremely difficult. So, its is assumed that these interaction forces are of a hydraulic character. They are proportional to the molecule *x*-component velocity (measured in relation to the fixed compression plate). *B* – is the hydraulic factor, *step*(…) – is the standard VCL-function. Expression (2) – is the step-function distributed in the 1 mm interval. It means that as soon as a molecule gets into the working surface of the fixed compression plate of the laboratory machine, the contact force grows continuously (within the 1 mm interval) from zero to its maximum value. Initially there is the clearance (between the fixed plate and the bar) equal to 0.1 mm, i.e. $x_{left} = -0.1$ (mm).

$$F_{jright} = -B(\dot{x}_j - v_0)step(x_j - x_{right},0,0,1,1); \tag{3}$$

- is correspondingly the force of the molecule interaction with the right movable compression plate of the laboratory machine. The plate motion law is $x_{right} = -v_0 t + 30.1$ (mm). Initial clearance is 0.1 (mm), v_0 – is the constant velocity of the movable compression plate.

$$F_{jk}(x_{jk}) = A(x_{jk} - a_1)^p [\prod_{i=1}^{7}(x_{jk} - a_i)]step(x_{jk},2sl,1,2l,0) + f\dot{x}_{jk}; \tag{4}$$

- is the molecule force characteristic. It is the force of interaction between the two molecules depending on the distance x_{jk} between them. a_i – is the root of the force characteristic. The force characteristic has the two components: the positional component and the damping component. *A* – is the force factor, *f* – is the damping factor. (**Author's note**: The $\dot{x}_{jk}$ time differentiation point is hardly seen in the last term of this formula). The simulation shows that the integration (1) becomes practically impossible, if the damping component (4) is not taken into account. The value pair (*A, f*) – is the required duralumin characteristic.

During high-ratio compression, each molecule can get into the vicinity of any other one. So, "each-one-with-each-one" interaction shall be taken into account. It is assumed that any two molecules start their interaction, if they are no more than 2*l*-distance away from each other. This interaction logics is determined by the *step*-function also. This function is a cubic polynomial of the following form:

$$\begin{gathered} y = ax^3 + bx^2 + cx + d; \\ x \in [2sl,2l]; s \in (0.5,1.0); \\ q = -\frac{(s-1)^3}{2}; a = \frac{1}{ql^3}; b = -\frac{3(1+s)}{2ql^2}; c = \frac{3s}{ql}; d = \frac{1-3s}{2q}; \end{gathered} \tag{5}$$

where *s* – is the parameter characterizing the decrease rate of the positional component of the molecule force characteristic (4) within the [*l*, 2*l*] interval.

Figure 6 specifies the assumed form of the positional component of the molecule force

characteristic. Usually [6], the force characteristic is assumed to be a unimodal and monotonous one in the [l, $2l$] interval (see Lennard-Jones potential, Morse potential, etc. [6]).

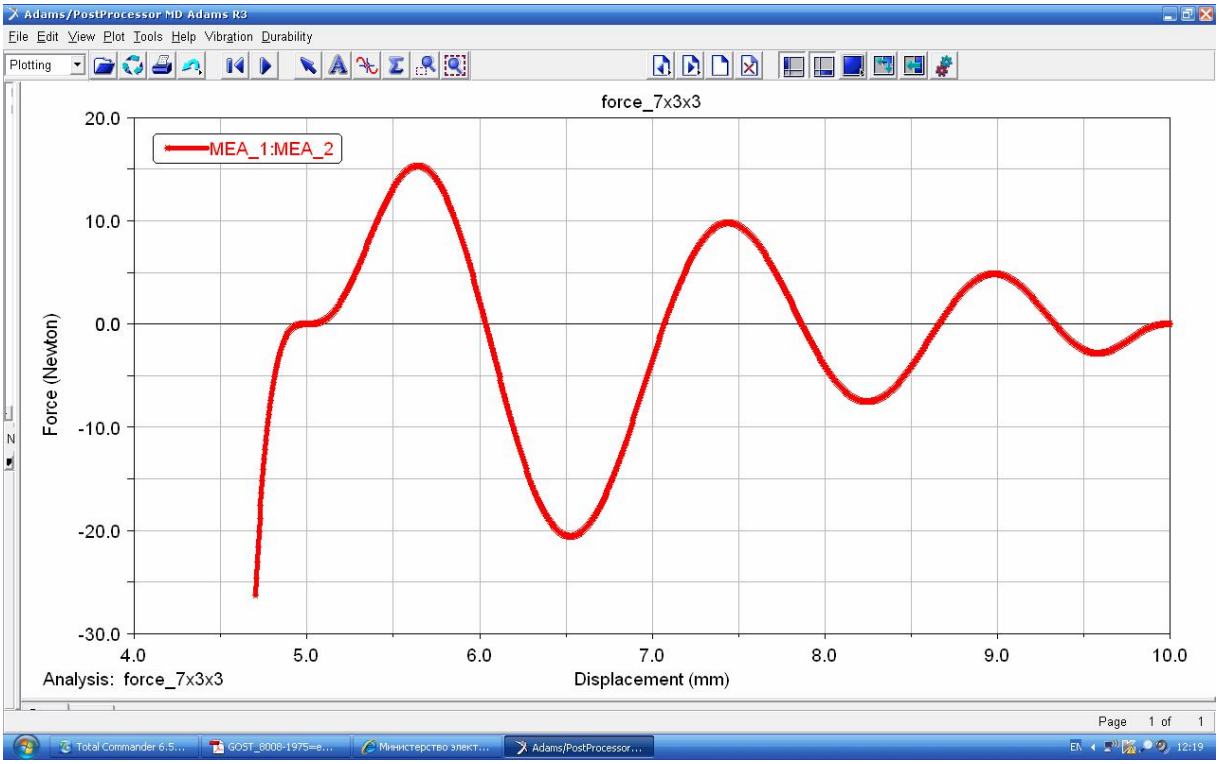

Figure 6: The assumed seven-root force characteristic for the 7x3x3=63 variant, l=5 mm

The work [7] shows, that using a monotonous force characteristic makes the initial equilibrium state of the model impossible ("shrinkage" effect). That is why the seven-root molecule force characteristic is proposed. It provides initial static equilibrium of the neighboring molecules arranged (along the edges and diagonals of the design lattice) correspondingly l, $l\sqrt{2}$, $l\sqrt{3}$ and $2l$-distance away from each other. These are the first 4 roots of the curve. The inserted equilibrium states are stable, if corresponding derivatives of their force characteristic are positive (see figure 7). So, 3 additional intermediate roots (and 3 corresponding equilibrium states) shall appear. These 3 additional roots are taken in the middle between the two neighboring roots. Finally, the required 7 roots are available:

$$a_1 = l; a_2 = \frac{l(\sqrt{2}+1)}{2}; a_3 = l\sqrt{2}; a_4 = \frac{l(\sqrt{2}+\sqrt{3})}{2}; a_5 = l\sqrt{3}; a_6 = \frac{l(\sqrt{3}+2)}{2}; a_7 = 2l; \quad (6)$$

The obtained force characteristic (4) has a power type. It is the product of binomials. There are two control parameters: p – determines the curve growth rate, s (see (5) also) – determines its decrease rate.

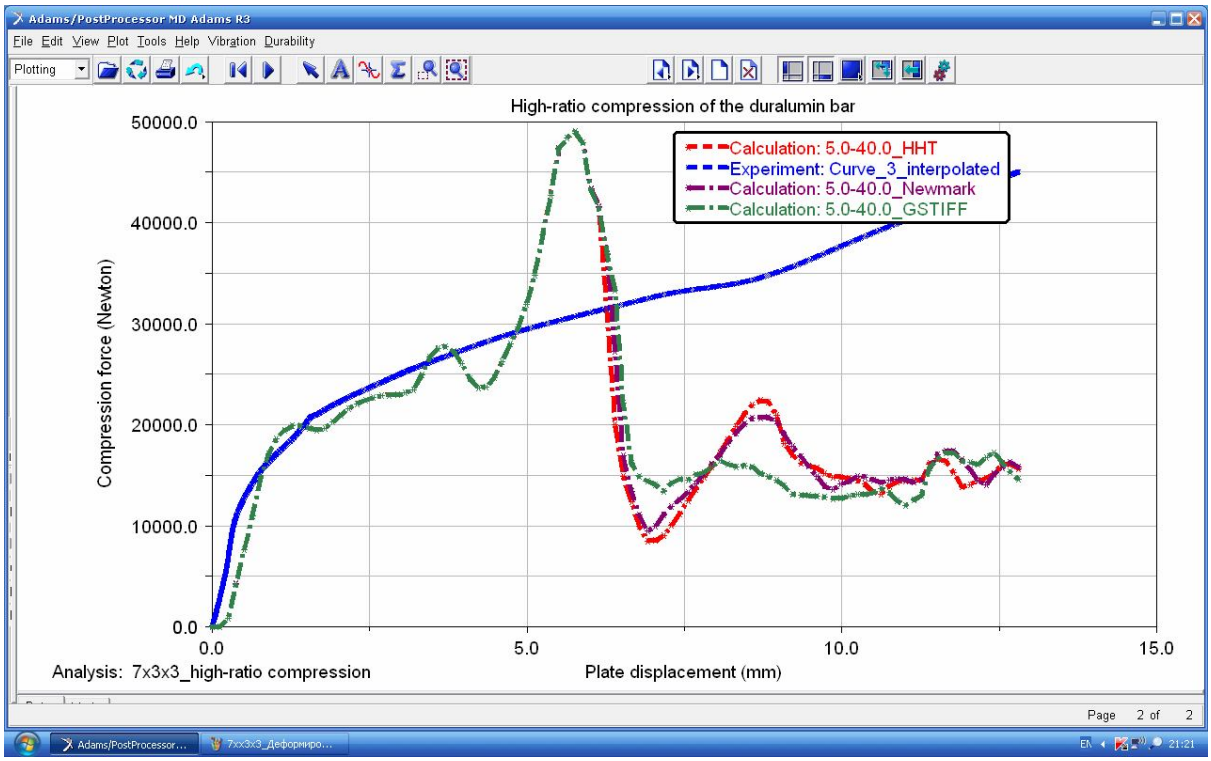

Figure 7: The first half of the calculation compression curve is close to the experiment compression curve. HHT, Newmark and GSTIFF integrators are compared

Figure 7 specifies a regular 7×3×3=63 bar-compression simulation result obtained using the MSC.Adams software. The model A and f parameters are selected under condition that the experiment compression curve (the solid monotonous line) and the calculation compression curve (the broken lines) are as close as possible. The calculation curve has an oscillation character. The discrepancy is acceptable only for the first half of the calculation curve providing approximately total 20% compression. At the same time, in practice 22% elongation is the usual guaranteed duralumin breaking limit [2]. The buckling process is so intensive, that the integration step becomes too small to continue the compression procedure. Three built-in integrators are compared: HHT, GSTIFF and Newmark. They all are acceptable. But the HHT seems to be the most effective one for this problem.

Figure 8 illustrates the calculated moment of the 20% compression of the 10×4×4=160 model of the duralumin bar. The fold is available, the buckling process is at the beginning. Calculation parameters are: A= 100.0 (N/mm^9), f=10 (N×sec/mm), B (hydraulic factor)=5×10^6 (N×sec/mm), s=0.99, p=2, l=3.3333 (mm), ρ (duralumin density) = 2800×10^{-9} (kg/mm^3),

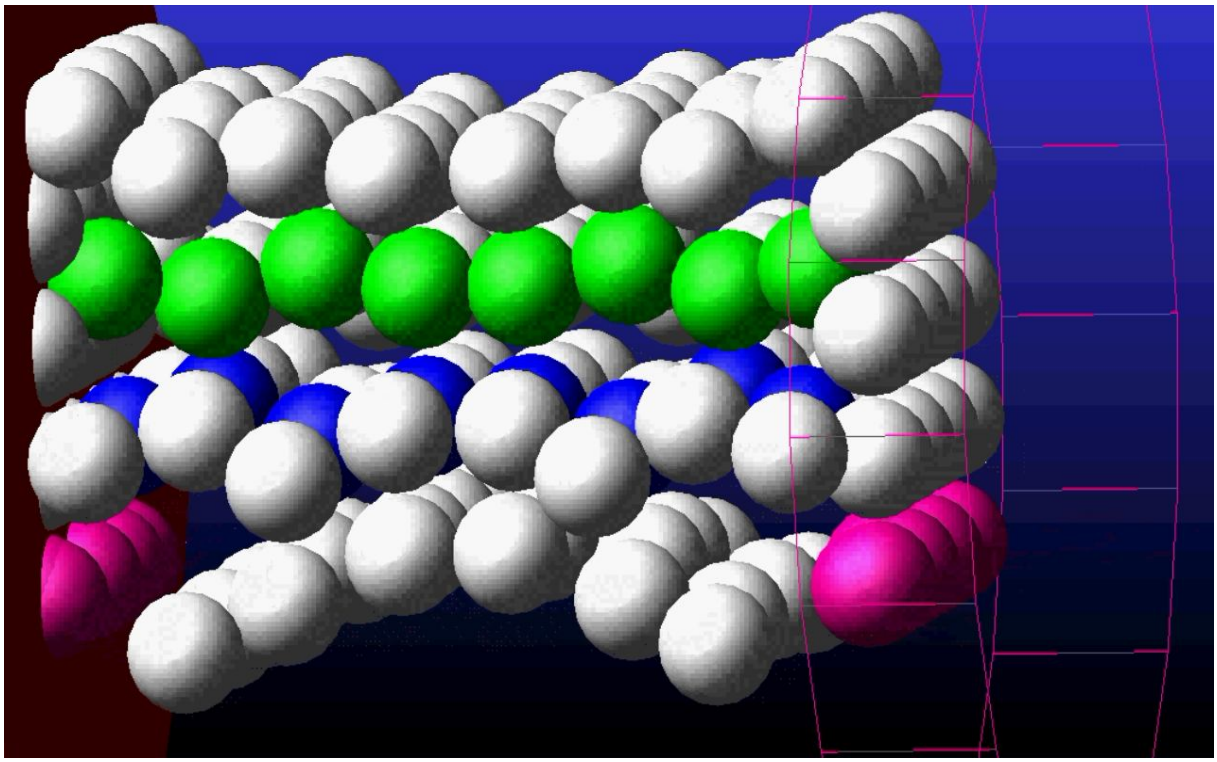

Figure 8: Calculated moment of the 20% compression of the 10x4x4=160 model of the duralumin bar. The fold appears in the bottom face. Two red defect lines are available in the vicinity of the compression plates.

R (molecule radius) = 1.648 (mm). For the regular 64-bit Windows 7, 24 Gb core memory and 3.1 GHz processing speed computer facilities , this variant requires ¾ of an hour.

CONCLUSIONS

- The proposed simulation model is made of a relatively small number of macro-molecules arranged in the nodes of the design lattice. The considered duralumin macro-molecule force characteristic is a seven-root polynomial.
- The duralumin macro-molecule force characteristic is selected under condition that the bar calculation compression curve and the bar experiment compression curve are as close as possible. But their discrepancy is acceptable only for the first half of the considered 40% compression interval. So, the proposed simulation model requires its further adjustment.

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